



Probabilistic design of wind turbine blades

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- Introduction
- Reliability-based design of wind turbines
- Reliability of blade with defects
 - Example - ULS
- Calibration of safety factors
 - Example – Fatigue
- Summary / conclusions





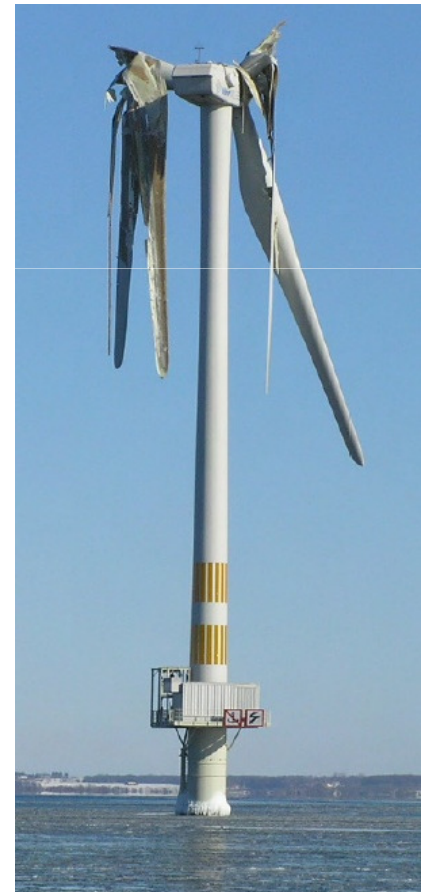
Introduction

Goal: minimize the total expected life-cycle costs
→ minimize COE

Initial costs: dependent on **reliability** level

O&M costs: dependent on O&M strategy,
availability and **reliability**

Failure costs: dependent on **reliability**





Introduction

Research projects:

- **UpWind (EC) – Integrated wind turbine design**
 - Uncertainty modeling and reliability / standards
- **Probabilistic Design of Wind Turbines (DSF)**
- **Reliability-based analysis applied for reduction of cost of energy for offshore wind turbines (DSF)**
 - Reliability-based analysis and design of wind turbine blades
 - Risk-based operation and maintenance of offshore wind turbines
 - Reliability-based design of wind turbine foundations
- **Norwegian Centre for Offshore Wind Energy (NORCOWE)**
 - Reliability analysis of wind turbines - basis for O&M planning
 - Risk-based operation and maintenance of offshore wind farms





Reliability modeling of wind turbines

Analysis of failure probabilities based on different types of information:

- Observed failure rates
Classical reliability theory

- Probabilistic models → failure probabilities

Structural Reliability Theory:

- Limit state equations
- Stochastic models for uncertain parameters
- Failure probabilities by FORM / SORM / simulation

Mechanical / electrical components

Structural components



Reliability-based design

Challenges by Probabilistic / reliability-based design:

- Limit state equations – related to design equations
- Stochastic models for uncertain parameters
- System modelling
- Target / minimum reliability level

Benefits by Probabilistic / reliability-based design:

- Optimal design for each component → uniform reliability
- Uncertainties related to the specific site, component and manufacturing process can be used
- Information from tests / monitoring can be taken into account in a rational way – by a Bayesian statistical approach



Reliability-based design

System aspects

- Series / parallel system?
- Damage tolerance
- Robustness



Robustness (system reliability) can be increased by

- Increased redundancy
 - mechanical load sharing
 - statistical parallel system effects
- Increased ductility
- Protecting the wind turbine to (unforeseen) incidents and defects
- Good quality control in all phases



Reliability-based design

Target / minimum reliability level:

- Building codes: e.g. Eurocode EN1990:2002:
 - annual $P_F = 10^{-6}$
- IEC 61400-1 & -3: wind turbines
 - annual $P_F \sim 10^{-4} - 10^{-3}$
- Observation of failure rates for wind turbines
 - Failure of blades: approx. $10^{-4} - 10^{-3}$ per year
 - Wind turbine collapse: approx. $10^{-5} - 10^{-4}$ per year



Design wind turbine (component) such that

- Probability of failure $P_F \leq \max P_F$



Reliability-based design of blades

- Combination of
 - Theoretical & computational models
 - Tests of coupons / materials
 - Tests of subcomponents
 - Few full-scale tests
 - Information from prototype wind turbines
 - Quality control / NDI
 - Measurements of climatic conditions
- Information are subject to physical, model, statistical and measurement uncertainties
- Uncertainties can be assessed and combined by use of *Bayesian statistical methods* for use in probabilistic design.



Reliability of blades – with defects

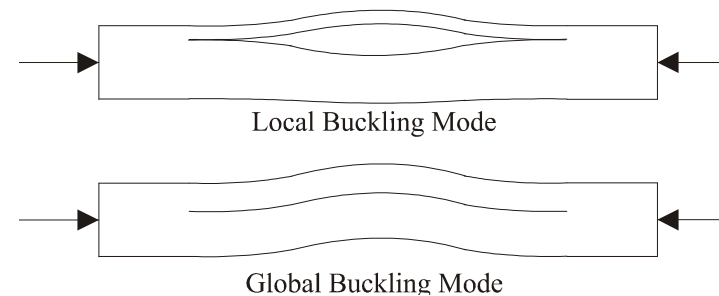
Local production defects:

- Delaminations
- Wrinkles
- Matrix cracks
- Voids
- Defects in glued joints
- ...

Model parameters:

- Type of defect
- Size of defect
- Position of defect

Delaminations:



Reliability of blades – with defects



Uncertainties in calculation of the load carrying capacity for wind turbine blades

1. Material properties

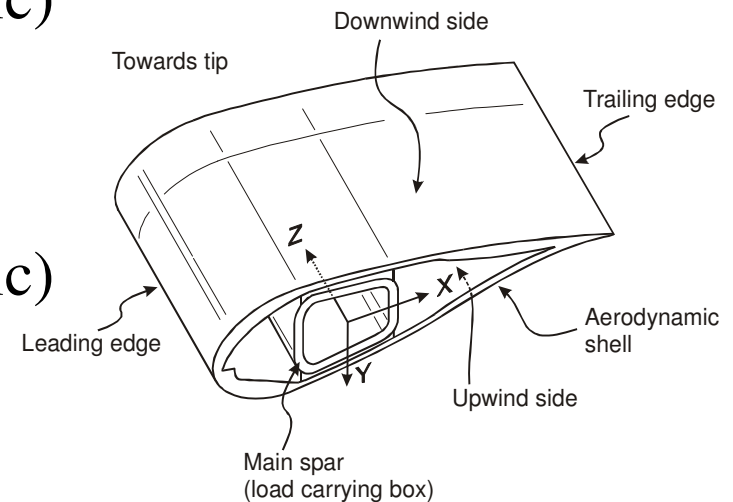
- Physical uncertainty (Aleatory)
- Statistical uncertainty (Epistemic)

2. Finite Element calculation

- Model uncertainty (Epistemic)

3. Failure criteria

- Model Uncertainty (Epistemic)



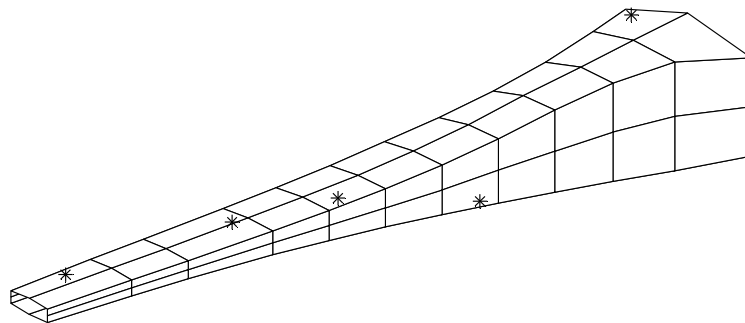
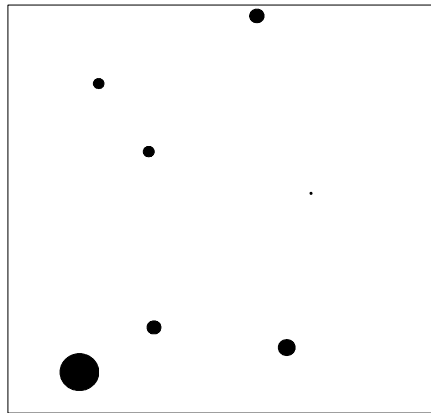
Reliability of blades – with defects

- Stochastic model for Defects



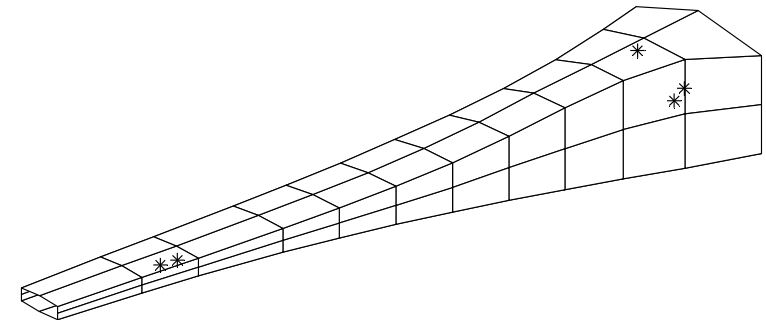
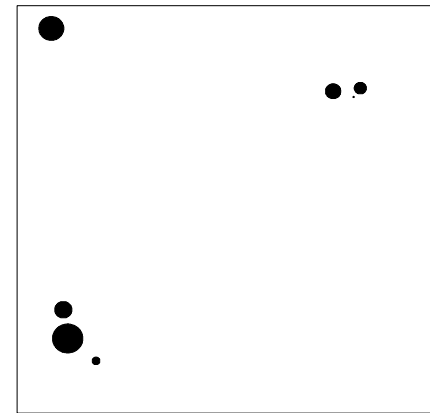
Model 1

Completely Random Distribution



Model 2

Random Cluster Distribution

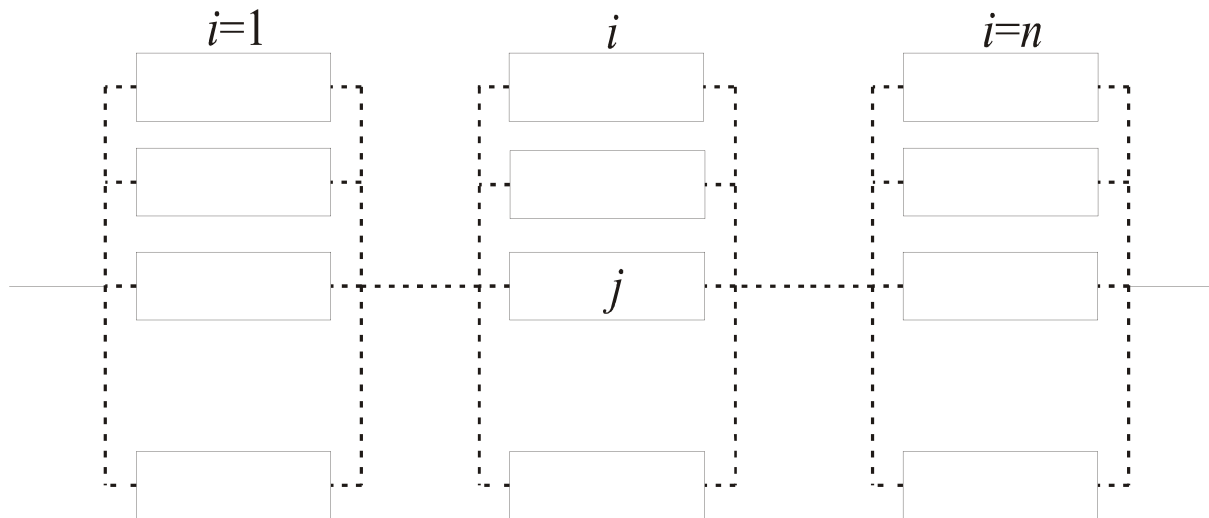


Reliability of blades – with defects

- System reliability



System model of wind turbine blade:



Probability of failure for the system:

$$P_F = P\left(\bigcup_{i=1}^n \bigcap_{j=1}^m (g_{ij} \leq 0)\right)$$

Reliability of blades – with defects

- Load Carrying Capacity of Main Spar



Failure of components by:

- Maximum Strain
- First Ply Failure

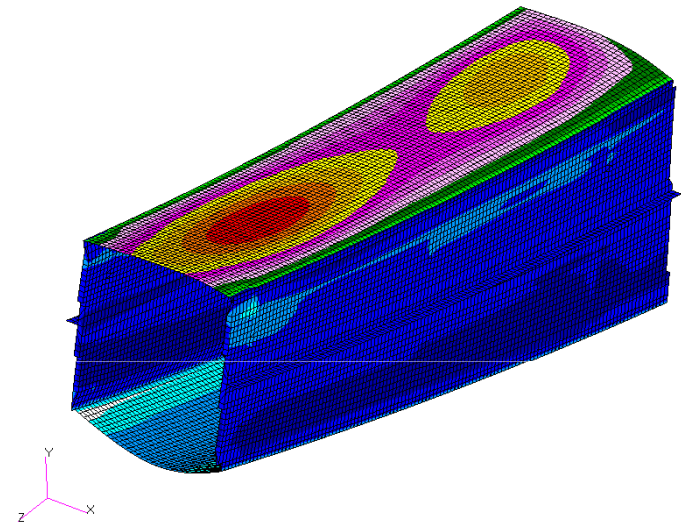
Limit state function for component
including the influence of a defect:

$$g(\alpha) = zX_R \alpha R(\epsilon_{\max}, \mathbf{E}) - X_L L$$

α strength reduction due to defect

Probability of failure for a component including defects:

$$P_{F,component} = \sum_{\alpha} P(g(\alpha) \leq 0) P(\alpha)$$



Reliability of blades – with defects

- Non Destructive Inspection (NDI)



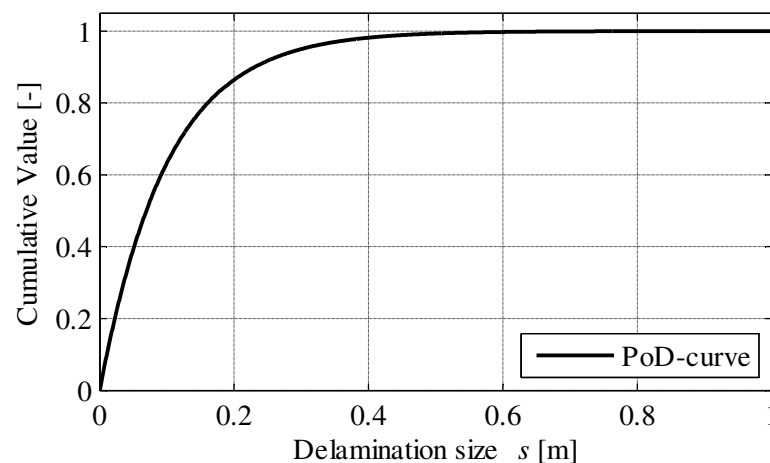
Updated probability of failure for a component:

$$P_{F_{\delta}, component} = \sum_{\alpha} \left[P(g(\alpha=1) \leq 0) PoD(\alpha) + P(g(\alpha) \leq 0) (1 - PoD(\alpha)) \right] P(\alpha)$$

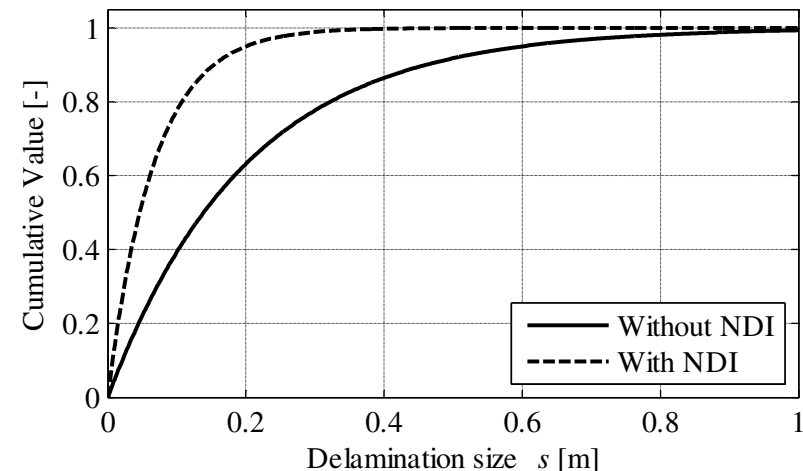
- Defects are assumed perfect repaired if detected by NDI

POD-curve:

Probability of Detection



Distribution function of defect size
without / with NDI



Reliability of blades – with defects



Example

- Average 1 defect per blade
- Average delamination size: 20 cm
- Average size minimum detectable delamination: 10 cm

Parameter	Value	Description
n	5	Number of parallel systems
m	5	Number of components in each parallel system
λ	1.0	Model 1: Average number of defects
χ_s	5.0m^{-1}	Average delamination size $\mu_s = 1/\chi_s$
χ_δ	10.0m^{-1}	Average NDI size $\mu_\delta = 1/\chi_\delta$

Reliability of blades – with defects

Example



Description	Defects	P_F	β
Reference	No defects	$3.1 \cdot 10^{-3}$	2.74
Reference	Model 1	$11.7 \cdot 10^{-3}$	2.27
Reference, NDI	Model 1	$4.6 \cdot 10^{-3}$	2.61
Larger system: $n = 5, m = 8$	Model 1	$6.7 \cdot 10^{-3}$	2.48
Less reliable NDI: $\chi_\delta = 5\text{m}^{-1}$, <i>NDI</i>	Model 1	$6.0 \cdot 10^{-3}$	2.51
More defects: $\lambda = 2$	Model 1	$21.8 \cdot 10^{-3}$	2.02

Calibration of partial safety factors



Partial safety factors (psf) for loads and strength parameters can be calibrated to a given reliability level taking into account:

- Uncertainty on loads
- Uncertainty on strength parameters
- Model uncertainty for computational model & failure criteria
- Statistical uncertainty (number of tests)

such that less uncertainty \rightarrow less partial safety factors \rightarrow **cost reduction**

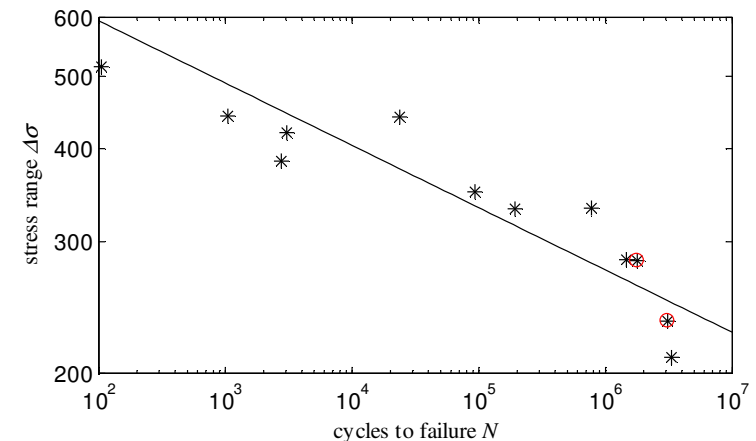
Uniform reliability \rightarrow **cost reduction**

Example - calibration of psf - fatigue



Uncertainties:

- Physical uncertainty - SN-curves
- Statistical uncertainty - limited number of tests
 - Bayesian modelling
- Model uncertainty - Miners rule



Linear SN-curve:

$$N = K \Delta\sigma^{-m}$$

$$\log N = \log K - m \log \Delta\sigma$$

Physical + Statistical uncertainty:

$\log K$

Bayesian statistics

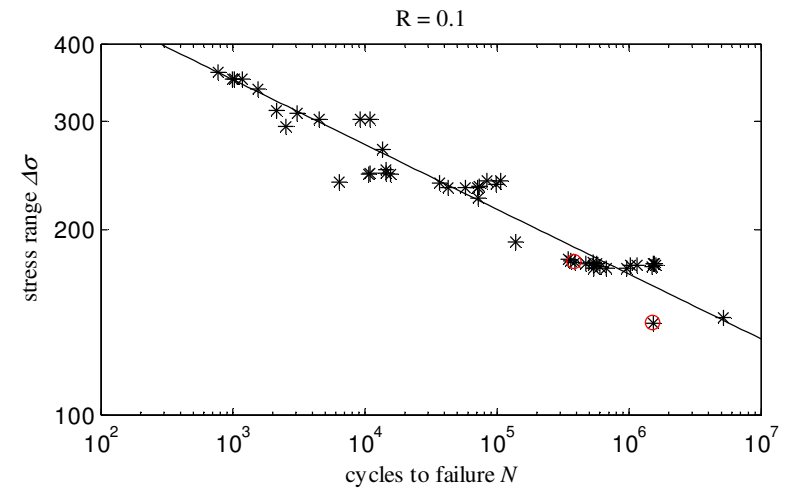
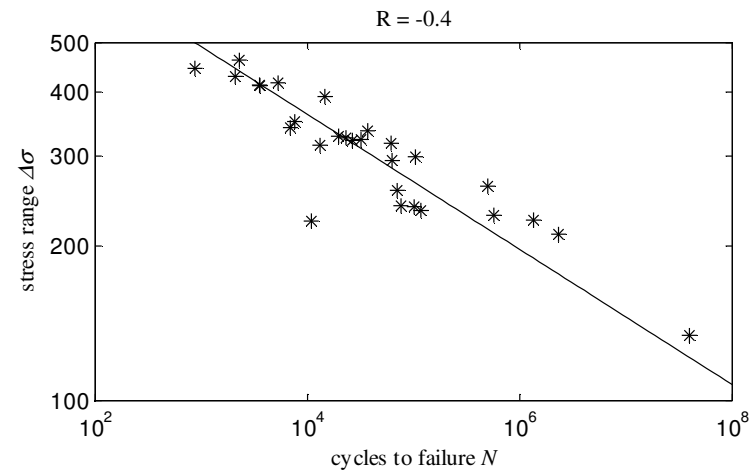
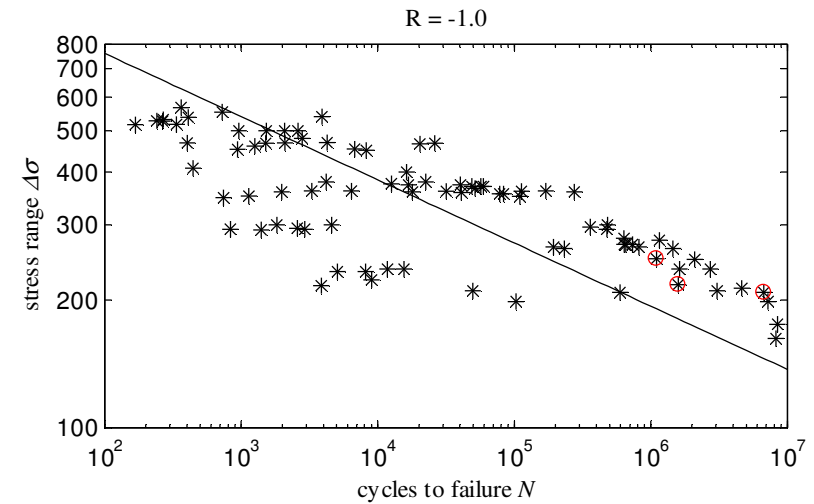
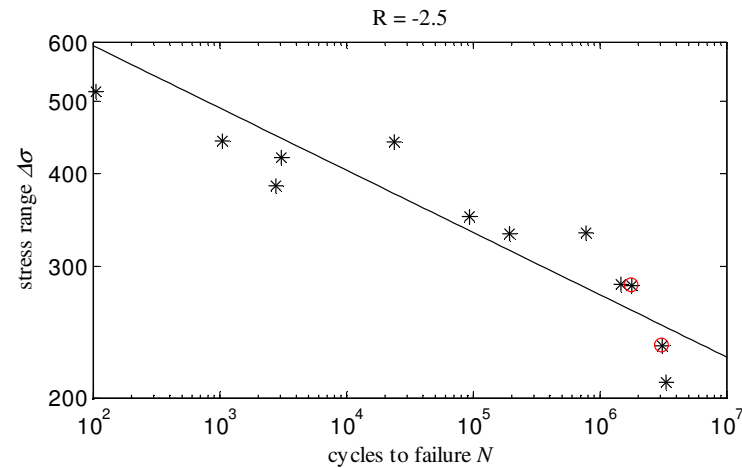
Example - calibration of psf - fatigue



OPTIDAT database: geometry R04 MD

R -ratio	Number of tests	Number of run-outs	m	$\log K$	$\sigma_{\log K}$
0.5	15	0	10.5	27.8	0.36
0.1	45	2	9.5	27.2	0.26
-0.4	28	0	7.6	23.4	0.44
-1.0	84	3	6.7	21.4	0.88
-2.5	10	2	12.0	35.2	0.63
10.0	34	0	22.2	58.7	0.64
2.0	6	3	29.7	73.8	0.35

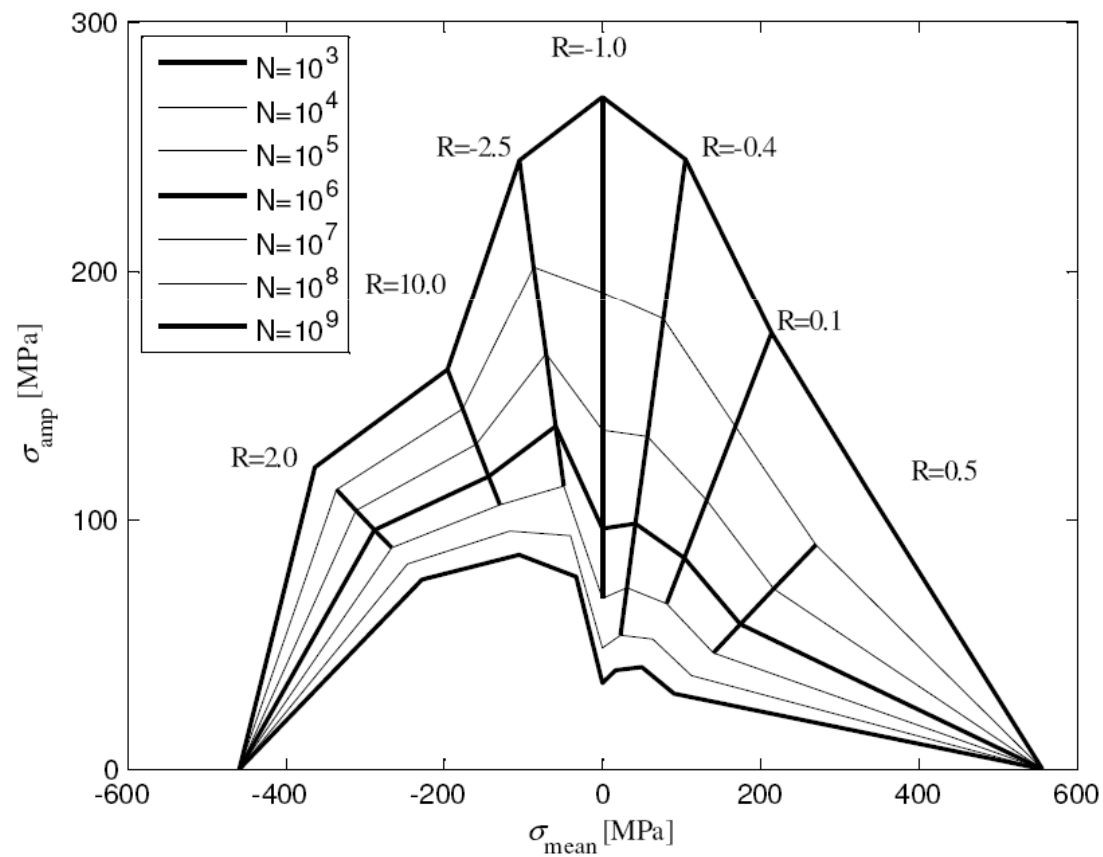
Example - calibration of psf - fatigue



Example - calibration of psf - fatigue



Constant life diagram for geometry R04 MD



Example - calibration of psf - fatigue



Variable amplitude fatigue tests

Load spectrum: Wisper and Wisperx

Miners rule for linear damage accumulation:

$$D = \sum_{i=1}^n \frac{1}{N(\Delta\sigma_i)}$$

Limit state equation:

$$g = \Delta - \sum_{i=1}^n \frac{1}{N(\Delta\sigma_i)}$$

Δ *model uncertainty: LN*(μ_Δ , σ_Δ)

Example - calibration of psf - fatigue



Variable	Description	Dist.	Mean	Std.
Δ	Uncertainty Miners Rule	LN	0.55	0.49
X_{exp}	Model Uncertainty – Exposure	LN	1.00	0.05
X_{aero}	Model Uncertainty – Aerodynamics	LN	1.00	0.10
X_{dyn}	Model Uncertainty - Dynamic Response	LN	1.00	0.05
X_{stress}	Model Uncertainty - Stress Calculation	LN	1.00	0.03
X_{stat}	Statistical Uncertainty - Load Assessment	LN	1.00	0.024
$\log K$	Physical Uncertainty SN-curve	N	27.768	0.358
m	Parameter SN-curve	D	10.541	-
V_{th}	Load cycles per year	D	$2.88 \cdot 10^6$	-
T	Life time in years	D	20	-



Example - calibration of psf - fatigue

Partial safety factors calibrated to a reliability index $\beta = 3.1$:

IEC 61400-1:

$$\gamma_n \gamma_m = 1.38$$

	$\gamma_n \gamma_m$
Reference	1.37
Uncertainty Miners rule	
$\Delta \sim \text{LN}(1.00;0.30)$	1.23
$\Delta \sim \text{LN}(0.90;0.55)$	1.27
$\Delta \sim \text{LN}(0.45;0.40)$	1.39
Model uncertainty aerodynamic	
$X_{aero} \sim \text{LN}(1.00;0.05)$	1.32
$X_{aero} \sim \text{LN}(0.95;0.10)$	1.31
Model uncertainty SN-curve	
$\log K \sim \text{N}(27.768;0.200)$	1.34



Summary / Conclusions

- Basis for reliability-based / probabilistic design
- Reliability analysis of blades with defects
 - Updating by NDI and Bayesian methods
 - Illustrated by example – extreme load
- Calibration of partial safety factors
 - Illustrated by example – fatigue

Future work

- Stochastic models for probabilistic design to be ‘standardized’
- Stochastic modelling of defects – for ‘real’ blades
- Reliability-based calibration of partial safety factors using test results at different levels by Bayesian methods
- Reliability-based test planning



Thank You For Your Attention

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Henrik S Toft, Aalborg University